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4. NAME AND ADDRESS OF INSTITUTION: Department of Electrical Engineering
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6. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT DURING THIS REPORTING PERIOD

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7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER NASA SPONSORSHIP DURING THIS REPORTING PERIOD INCLUDING JOURNAL REFERENCES:

Summary of Research Results

The design of an optimal CMG (Control moment gyro) momentum management and attitude control system for a large-scale system using a multi-stage design process has been accomplised. The designed controller enables to place the eigenvalues of the closed-loop system within a specific region of the complex plane and simultaneously minimize a quadratic performance index.

For implementation of the optimal analog controller using microprocessors or microcomputers, new digital redesign techniques have been developed to digitize the analog controller.

The developed sequentially decoupling design method can be applied to a general large-scale system for optimal and robust control.

Based on the research results in the period of 1989-1991, we have published the following papers in the referred journals:

1. Shieh, L.S., X.M.Zhao, J. L. Zhang, "Locally Optimal-digital Redesign of Continuous-time Systems," *IEEE Trans. Industrial Electronics*, Vol.36, No.4, pp.511-515, November,1989.

Abstract

This paper presents a new optimal digital redesign technique for finding a dynamic digital control law from the given continuous-time counterpart by minimizing a local quadratic performance index. The quadratic performance index is chosen as the integral of the weighted squared difference between the states of the original closed- loop system and those of the digitally controlled closed-loop system at any instant between each sampling period. The developed optimal digital redesign control law enables the states of the digitally controlled closed-loop system to closely match those of the original closed-loop system at any instant between each sampling period, and it can easily be implemented using microcomputer with a relatively large sampling period.

2. Shieh, L.S., Z.Liu, and N.P. Coleman,"Design of Linear Quadratic Regulators with Eigenvalue Placement in a Specified Region," *Control Theory and Advanced Technology*, (Japan), Vol.6, No.1, pp.93-110, 1990.

Abstract

Two linear quadratic regulators are developed for placing the closed-loop poles of linear multivariable continuous-time systems within the common region of an open sector, bounded by lines inclined at $\pm \pi/2k$ (for a specified integer $k \geq 1$) from the negative real axis, and the left-hand side of a line parallel to the imaginary axis in the complex s -plan, and simultaneously minimizing a quadratic performance index. The design procedure mainly involves the solution of either Lyapunov equations or Riccati equations. The general expression for finding the lower bound of a constant gain γ is also developed.

3. Shieh,L.S., J.L.Zhang, and S.Ganesan, "Pseudo-continuous-time Quadratic Regulators with Pole Placement in a Specific Region," *Proceedings of the IEE (Egnland) Part D, Control Theory and Applications*, Vol.137, No.5, pp.297-301, 1990.

Abstract

The paper comments on the pseudo-continuous-time quadratic regulator developed in an earlier paper. It also presents a new digital redesign technique, based on matching all the states at all the sampling instants, for finding the pseudo-continuous-time quadratic regulator.

4. J.W. Sunkel and L.S. Shieh, "Optimal Momentum Management Controller for the Space Station," *AIAA Journal of Guidance, Control and Dynamics*, Vol.13, No.4, pp.659-688, July-August, 1990.

Abstract

This paper presents a new sequential design procedure for determining an optimal control moment gyro momentum management and attitude control system for Space Station Freedom. First, the space station equations of motion are linearized and uncoupled, and the associated state space equations are defined. Next, a new sequential procedure is used for the development of a linear quadratic regulator with eigenvalue placement in a specified region of the complex plane. The regional pole assignment method is used since it is best suited for tradeoffs between eigenvalue locations and robustness with respect to parameter variations, sensor failures, implementation accuracies, and gain reduction. The matrix sign function is used for solving the Riccati equations, which appear in the design procedure. Simulation results are given which show that the resultant design provides desired system performance.

5. Shieh,L.S., X.M. Zhao,N.P. Coleman,and J.W. Sunkel, "Two-stage Suboptimal Discrete-time Regulators for Continuous-time Stiff Dynamic Systems," *Applied Mathematical Modelling* , Vol.14, pp.199-211, April 1990.

Abstract

A two-stage method is developed for design of linear quadratic regulators (LQRs) with regional pole assignment for a large-scale continuous-time stiff dynamic system and its observer, which do not exhibit a two-time scale structure explicitly. The method also provides a procedure to convert the designed analog LQR and observer to an equivalent digital LQR and observer, respectively, for digital implementations. First, the large-scale stiff dynamic system is block-decomposed into two block-decoupled subsystems according to their own characteristics via the fast and stabel matrix sign algorithm. Next, a sequential design procedure is used to design a LQR with regional pole placement for each subsystem. The same procedure is then carried out to design an optimal observer. For implementation of the designed analog LQR using a digital LQR, the designed analog LQR and observer are converted into an equivalent digital LQR and observer, respectively, via a digital redesigned method. A practical stiff system is used as an illustrative example to demonstrate the effectiveness of the proposed method.

6. Chyi Hwang, Ming-Jeng Lu, and Leang S. Shieh, "Improved FFT-based Numerical Inversion of Laplace Transforms via Fast Hartley Transform Algorithm," *Computers Math. Applic.*, Vol.22, No.1, pp.13-24, 1991

Abstract

The disadvantages of numerical inversion of the Laplace transform via the conventional fast Fourier transform (FFT) are identified and an improved method is presented to

remedy them. The improved method is based on introducing a new integration step length $\Delta\omega = \pi/mT$ for trapezoidal-rule approximation of the Bromwich integral, in which a new parameter m, is introduced for controlling the accuracy of the numerical integration. Naturally, this method leads to muiltiple sets of complex FFT computations. A new inversion formula is derived such that N equally-spaced samples of the inverse Laplace transform function can be obtained by $[m/2] + 1$ sets of N-point complex FFT computations or by m sets of real fast Hartley transform (FHT) computations.

7. Leang S.Shieh, Xiao M.Zhao and John W.Sunkel, "Hybrid State-space Self-tuning Control Using Dual-rate Sampling," *IEE Proceedings – D*, Vol.138, No.1, pp.50-58, January 1991.

Abstract

This paper presents a hybrid state-space self-tuning control scheme using dual-rate sampling for suboptimal digital adaptive control of linear time-invariant continuous-time multivariable stochastic systems with unknown parameters. An equivalent fast-rate discrete-time state-space innovation model (with estimated states) of the continuous-time system is constructed by using the estimated system parameters and Kalman gain. To utilise the existing optimal regional-pole assignment method developed in the continuous-time domain, the constructed fast-rate discrete-time model is converted into an equivalent continuous-time model for the development of a state-feedback optimal control law with pole placement in a specific region. The developed analogue optimal control law is then converted into an equivalent pseudo-slow- rate digital control law via the proposed digital redesign technique, which can be realised via slow-rate digital electronics. The proposed method enables the development of a digitally implementable advanced control algorithm for digital adaptive control of continuous-time multivariable stochastic systems which may be unstable and/or have nonminimum phase.

8. Chyi Hwang, Tong-Yi Guo and Leang-San Shieh, "A Canonical State-space Representation for SISO Systems Using Multipoint Jordan CFE," *Journal of theFranklin Institute* Vol.328, No. 2/3, pp. 207-216, 1991.

Abstract

A canonical state-space realization based on the multipoint Jordan continued-fraction expansion (CFE) is presented for single-input-single-output (SISO) systems. The similarity transformation matrix which relates the new canonical form to the phase-variable canonical form is also derived. The presented canonical state-space representation is particularly attractive for the application of SISO system theory in which a reduced-dimensional time-domain model is necessary.

9. Sekar Ganesan, Leang S. Shieh and Mohanad M. Mehio, "Sequential Design of Linear Quadratic State Regulators with Prescribed Eigenvalues and Specified Relative Stability," *Computers Math.Applic.* Vol.21, No.4, pp.1-10, 1991

Abstract

A digital redesign technique is developed for determining the digital version of an optimal momentum management controller previously designed by the authors for the Space Station Freedom. The technique matches the continuous-time and discrete-time states at all sampling instants to find a pseudo-continuous-time quadratic regulator from s continuous-time quadratic regulator. It is shown that the digital redesigned states closely match the continuous-time optimal states. It is also shown that the digital redesigned state-feedback control law based on the bilinear transformation method is a class fo the proposed control law. The digital redesign technique is then extended to find the digital version of the continuous-time optimal observer. It is shown that the states of the redesigned digital observer closely match those of the continuous-time optimal observer.

10. Leang S. Shieh and Jian L. Zhang, "Optimal Digital Redesign of Continuous-time Controllers," *Computers Math. Applic.*, Vol.22, No.1, pp.25-35,1991

Abstract

This paper proposes a new optimal digital redesign technique for finding a dynamic digital control law from the available analog counterpart and simultaneously minimizing a quadratic performance index. The proposed technique can be applied to a system with a more general class of reference inputs, and the developed digital regulator can be implemented using low cost microcomputers.

11. J.W.Sunkel, L.S.Shieh, "Multi-stage Design of An Optimal Momentum Management Controller for the Space Station," *AIAA J. of Guidance, Control, and Dynamics*, Vol.14, No.3, pp.492-502,1991

Abstract

This paper presents a multi-stage design scheme for determining an optimal control moment gyro momentum management and attitude control system for the Space Station Freedom. First, the Space Station equations of motion are linearized and then block-decomposed into two block- decoupled subsystems using the matrix sign algorithm. Next, a sequential design procedure is utilized for designing a linear quadratic regulator for each subsystem, which optimally places the eigenvalues of the closed-loop subsystem in the region of an open sector, bounded by lines inclined at $\pm\pi/2k$ (for k =2 or 3) from the negative real axis, and the left-hand side of a line paralled to the imaginary axis in the s-plane. Simulation results are presented to compare the resultant designs.